AEROELASTIC STABILITY OF A FOUR-BLADED SEMI-ARTICULATED SOFT-INPLANE TILTROTOR MODEL

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Abstract. A new four-bladed, semi-articulated, soft-inplane rotor system, designed as a candidate for future heavy-lift rotorcraft, was tested at model scale on the Wing and Rotor Aeroelastic Testing System (WRATS), a 1/5-size aeroelastic wind-tunnel model based on the V-22. The experimental investigation included a hover test with the model in helicopter mode subject to ground resonance conditions, and a forward flight test with the model in airplane mode subject to whirl-flutter conditions. An active control system designed to augment system damping was also tested as part of this investigation. Results of this study indicate that the new four-bladed, soft-inplane rotor system in hover has adequate damping characteristics and is stable throughout its rotor-speed envelope. However, in airplane mode it produces very low damping in the key wing beam-bending mode, and has a low whirl-flutter stability boundary with respect to airspeed. The active control system was successful in augmenting the damping of the fundamental system modes, and was found to be robust with respect to changes in rotor speed and airspeed. Finally, conversion-mode dynamic loads were measured on the rotor and these were found to be significantly lower for the new soft-inplane hub than for the previous baseline stiff-inplane hub.

1 INTRODUCTION

Current tiltrotor designs for production aircraft use gimballed stiff-inplane rotor systems. Stiff-inplane rotor systems are desirable for tiltrotors because in hover there is no concern for ground resonance, and in high-speed airplane mode the stability boundaries associated with whirl-flutter have been established at velocities slightly beyond aircraft power limits, with adequate damping margins at subcritical airspeeds. The disadvantage of a stiff-inplane rotor system is that significant inplane dynamic blade loads may develop, particularly during maneuvers.

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Soft-inplane rotor systems can greatly reduce the inplane blade loads in tiltrotor aircraft, thereby reducing strength requirements for the hub, leading to reduced structural weight and improved aircraft agility. It is for similar reasons that conventional helicopters with three or more blades have soft-inplane rotor systems. However, soft-inplane rotor systems generally have reduced damping margins and lower stability boundaries than stiff-inplane rotor systems. Therefore, before soft-inplane rotor systems can be applied to tiltrotor aircraft, design concepts must be developed which can ensure adequate stability characteristics in both hover and forward flight.

One of the first soft-inplane tiltrotor designs to be proposed was the Boeing Model 222. Aeromechanical behavior of this soft-inplane hingeless rotor system was addressed in several experimental and analytical studies using different size rotor test apparatus, beginning with a 1/10-scale wind-tunnel model described in Ref. 1, and ending with a full-scale 26-ft. diameter semispan model tested in the NASA Ames 40- x 80-ft. tunnel described in Refs. 2 and 3. The Boeing soft-inplane design had a relatively high inplane natural frequency (about 0.9/rev at low airspeeds), such that the design rotor speed in hover mode did not create a ground resonance condition. The only experimental results associated with an instability of this configuration were obtained with the system in airplane mode subject to air resonance conditions. In general, this configuration (in airplane mode) exhibited unacceptably low damping in the wing beam mode at all airspeeds. In 2001, a gimballed-hub, soft-inplane rotor system was tested on the WRATS model in hover as described in Ref. 4. This rotor system had a fundamental lag frequency of 0.5/rev, and hover testing showed that aeromechanical instabilities could occur at rotor speeds well below the design rotor speed. As this system exhibited inadequate stability characteristics in hover, it was not tested in airplane mode.

More recently, a new full-scale, semi-articulated, soft-inplane rotor was designed by Bell Helicopter as part of the Army Variable Geometry Advanced Rotor Technology (VGART) program. The goals of the Bell VGART study were to satisfy Army Technical Effort Objectives for reduced weight, increased maneuverability, and reduced vibratory loads; and as part of the design to satisfy scalability issues and include growth potential to allow for more than three blades. The new soft-inplane rotor does not have a gimbal, but instead uses a standard flap hinge for the blades. It also adds a highly-damped elastomeric-bearing in the blade lag direction (the term semi-articulated is used because the lag mechanism with elastomeric-bearing has both hinge and flexural qualities). The inplane (lag) frequency of the rotor was designed to be in a range of 0.55/rev to 0.75/rev to maximize the dynamic loads reduction capabilities of the soft-inplane system while retaining feasibility for full-scale application. The new soft-inplane rotor also has four blades, rather than three as used on the previous stiff-inplane designs. Using the results from this VGART study, a new 1/5-size, four-bladed, soft-inplane hub was designed and fabricated for the WRATS tiltrotor model.

The new four-bladed, semi-articulated, soft-inplane rotor system was tested on the Wing and Rotor Aeroelastic Testing System (WRATS), a 1/5-size aeroelastic tiltrotor wind-tunnel model based on the V-22. The experimental investigation included a hover test with the model in helicopter mode subject to ground resonance conditions, and a forward flight test with the model in airplane mode subject to whirl-flutter conditions. The objectives of the investigation were to determine the damping margins, stability boundaries, and load reduction factors associated with the new soft-inplane rotor as compared to the current baseline stiff-inplane rotor system. Also included as part of this investigation was testing of an active control system designed to augment system damping. The three-bladed stiff-inplane rotor system (used in several past investigations documented in Refs. 5-8) was examined under the same conditions as the four-bladed soft-inplane hub to provide a baseline for comparison.

2 APPARATUS

The WRATS 1/5-size semi-span tiltrotor model was used as the test-bed for these experiments, and the important characteristics of this wind-tunnel model have been described in several previous reports such as Ref. 9, Ref. 10, and most recently Ref. 5. The wind-tunnel test was performed at the Langley Transonic Dynamics Tunnel (TDT), and the hover test was performed in a 30 x 30-ft. hover cell located in an adjacent high-bay building. While the TDT can use R-134a refrigerant as a test medium, the current experiment was conducted using air at atmospheric pressures.

The key geometric features of the new soft-inplane hub and the baseline stiff-inplane hub are illustrated in Fig. 1, and several important attributes of these rotor systems are listed in Table 1. Some significant features of the soft-inplane hub are a 0.5 inch pre-lead used to reduce the steady lag response associated with blade drag, a flap hinge offset of 1.76 inches ($e_\beta = 0.039$), and a lag pivot point of 5.76 inches ($e_\zeta = 0.126$). The outer pitch bearing is coincident with the lag pivot. As shown, the pitch links have been moved from a trailing-blade position on the three-bladed stiff-inplane hub to a leading-blade position on the four-bladed soft-inplane hub. Both hubs have a nominal geometric δ_3 (pitch-flap skew angle) of about 15°, but for the soft-inplane system flap-up movement produces pitch-down rotation while for the stiff-inplane hub flap-up movement produces pitch-up rotation. The pitch-flap and pitch-lag couplings for the soft-inplane hub were measured as a function of blade collective pitch position (collective measured at the 75% span station), and are plotted as the effective geometric δ_3 and δ_4 angles, respectively, in Fig. 2. The pitch-flap coupling is shown to change rapidly at low collectives where it has a higher than nominal value, but in the normal collective range associated with airplane mode (20° to 50°) the pitch-flap coupling remains in a $\pm 1°$ band about the nominal 15° value. The pitch-lag coupling is shown to be about 9° over the 20° to 50° collective range with about the same deviation band of $\pm 1°$, and lag (aft) movement produces a pitch-down rotation.

The four-bladed, soft-inplane rotor system had two sets of elastomeric dampers that were used in the tests so that the effects of lag mode frequency placement could be examined (the dampers provide both damping and stiffness to the lag hinge). The softer set of dampers produced a nominal lag mode frequency of 0.57/rev while the stiffer set of dampers produced a nominal lag mode of 0.63/rev (based on an 888 RPM design rotor speed in hover). Only the soft damper set was used in the hover test, while both sets were used in the wind-tunnel test.

3 HOVER TESTING

The four-bladed, soft-inplane rotor system was tested in both isolated-rotor and coupled-system configurations. For the isolated-rotor case the pylon was clamped to the rotor test stand such that the fixed-system frequencies were well above the rotor frequencies of interest, and for coupled-system testing the wing was cantilevered to the test stand with fundamental elastic wing bending modes free to interact with the rotor system. Frequencies of the three key coupled-system modes are plotted as a function of rotor speed in Fig. 3. The three modes are the rotor lag mode (with the 0.57/rev damper set installed), the wing beam mode, and the wing torsion/chord (WTC) mode. Coupling between the rotor lag and WTC modes increases as the lag mode frequency (nonrotating frame) approaches the WTC frequency at the upper rotor speed range (lag perturbation stick-stirs produce significant WTC response). Without sufficient damping, this condition will generally result in a ground resonance type instability. The coupled-system damping associated with these three modes is shown in Figs. 4, 5, and 6, where it is seen that there is no instability associated with any of the modes over the rotor speed range tested. A likely reason for these results is the high value of lag mode damping provided by the elastomeric damper as indicated in Fig. 4. For the isolated rotor the nominal value for damping is about 12% with little variation over rotor speed, while the coupled system the damping is generally higher and varies from 12% to 18% over the rotor speed range shown. The measured frequency of the rotor lag mode was approximately the same for the isolated and coupled configurations. An important result from the hover testing was that both the measured frequency and measured damping of the rotor lag mode are in close proximity to those expected for full-scale applications of soft-inplane tiltrotor systems.

It should be noted when viewing figures that most plots presented in this paper show error bars. This indicates that a minimum of 5 data points are available for the indicated condition, with the data point representing the average of the available records and the error bar indicating the standard deviation from the average. In some cases there were less data acquired, and for these cases the individual data records are shown (Figs. 5 and 6 for example). On most plots, faired lines (either linear or cubic spline) are used to help indicate the data trends.

The frequency of the WTC mode, which is the key wing mode associated with inplane hub motion and ground resonance behavior in hover, is about 5.6 Hz and remains steady with respect to rotor speed as shown in Fig. 3. Damping of this crucial mode is shown in Fig. 5 for two collective pitch settings, 0° and 10° as measured at the 75% radial station. As shown, the damping begins at about 2% critical in the lower rotor speed range, then falls to a minimum of about 1% at 800 RPM. The soft-inplane system did not encounter an instability under normal operating conditions. In previous studies with a soft-inplane gimballed rotor system (Ref. 4) the WTC mode was found to become unstable. Thus, it appears that the new semi-articulated hub design, with use of highly-damped elastomeric materials, provides adequate damping to avoid aeromechanical instability over the design rotor speed range.

The wing beam mode in hover is not highly coupled with the rotor lag mode (lag perturbation stick-stirs produce little wing beam response), and previous studies indicate that this mode is not likely to become unstable. However, as this is the lowest fixed-system mode (5.4 Hz natural frequency) it was monitored carefully throughout the hover test. Fig. 6 shows the damping associated with the wing beam mode as a function of rotor speed, and indeed this mode is more highly damped than the WTC mode (for $\Omega > 300$ RPM). The damping does, however, decrease with rotor speed from about 5% critical at the peak to about 2% critical at the upper end of the rotor speed spectrum.

Figs. 5 and 6 also show that, for the semi-articulated, soft-inplane rotor, the collective pitch setting has little effect on the WTC and wing beam mode dampings. This is contrary to the behavior observed for the gimballed, soft-inplane rotor system investigated in Ref. 4 where the blade pitch setting was found to have a significant impact on damping. The exact cause of the damping change with collective that was observed in Ref. 4 has yet to be determined, but may be associated with the particular design and not a general characteristic of gimballed soft-inplane rotor systems.

4 WIND-TUNNEL TESTING

The new four-bladed, soft-inplane rotor system, oriented in airplane mode for high-speed wind-tunnel testing, is shown in Fig. 7 mounted on the WRATS testbed in the NASA Langley Transonic Dynamics Tunnel (TDT). The basic dynamics of the wing/pylon/rotor system shifts substantially with conversion to airplane mode, as the mass offset of the pylon/rotor moves from above to forward of the elastic axis, and thus creates a significant coupling between the wing beam and torsion modes and the rotor lag mode. The wing chord mode becomes predominantly isolated from these modes in the airplane configuration.

For airplane-mode aeroelastic stability testing, the rotor system is normally operated windmilling (unpowered and disconnected from the drive system), with the collective blade pitch used to adjust the rotor speed, and a near-zero torque at the rotor shaft. This represents the most conservative manner to test the stability of the system (no damping from the drive system). Under windmilling operation, damping of the key mode associated with system stability (the wing beam mode) was determined to be significantly less for the new four-bladed soft-inplane hub than for the three-bladed stiff-inplane (baseline) system, as shown in Fig. 8. Damping of the wing beam mode was generally less than 1.0% in windmilling flight for all the soft-inplane configurations considered (on-downstop (D/S), off-D/S; 0.57/rev dampers, 0.63/rev dampers; 550, 742, and 888 RPM rotor speeds). Unfortunately, these damping characteristics are inadequate for full-scale operation.

In powered-mode (200 in-lb torque maintained) the system damping and the stability boundary both increased significantly as illustrated in Fig. 9 (note on-D/S configuration shown rather than off-D/S as used in Fig. 8 because of low damping associated with the off-D/S case). Although not a solution for the low-damping behavior associated with the windmilling condition, these results represent a substantial deviation from previous results associated with the baseline system, wherein the effect of power is not significant with respect to the stability boundary. Fig. 10 shows that while the subcritical damping values increase significantly with power for the stiff-inplane rotor system, the instability condition is about the same.

5 STABILITY AUGMENTATION TESTING

The active control system examined in this study incorporates wing-root bending measurements (strain gages) for feedback and applies control signals to three independent swashplate hydraulic actuators. The active control algorithm was developed cooperatively between Bell and NASA Langley, and is based on the Generalized Predictive Control (GPC) theory presented in Refs. 11 and 12. Past studies that have successfully demonstrated the stability augmentation capability of the GPC theory for tiltrotors are documented in Refs. 13 and 14.

The GPC active stability augmentation system was highly successful in application to both the new soft-inplane and the baseline stiff-inplane rotor systems in high-speed flight. Fig. 11 shows very significant increases in damping associated with closed-loop control of the baseline system that are extended well beyond the open-loop stability boundary. For the open-loop system the instability occurs at a velocity of about 105 kts. Closed-loop testing proceeded to a velocity of 150 kts. before testing was terminated, which is 45 kts. beyond the open-loop stability boundary (100 kts beyond for full-scale). In fact, the damping of the wing beam mode is shown to be increasing as a function of the airspeed, rather than decreasing, as is the custom for the open-loop system. Similar results were also obtained for the new soft-inplane rotor system as shown in Fig. 12, although the system was not tested as far beyond the stability boundary as the baseline system.

While not shown on a plot, damping of the wing chord and torsion modes also increased substantially under GPC, otherwise the system would eventually become unstable in these modes. Data were also acquired within the same run at several rotor speeds between 550 and 888 RPM, and the GPC control system was not adversely affected by these changes in rotor speed. Data from this test show that it is possible to attain the damping levels required for acceptable operation of a soft-inplane rotor system using GPC, and the control system shows robustness with respect to both rotor speed and airspeed deviations.

6 CONVERSION LOAD MEASUREMENTS

The last objective of this test was to demonstrate the reduction in hub and blade dynamic loads, which is the key benefit of using soft-inplane rotor systems. Blade and hub loads were measured for a defined set of pylon conversion angles (0, 15, 30, 45, 60, 75, and 90 degrees) and cyclic pitch settings (flapping up to 3 degrees) in combination, which are designed to simulate tiltrotor free-flight maneuvers. The dynamic loads at each instrumented blade station were measured for each of various flight conditions, and the maximum sustained dynamic loads (half-peak-to-peak of all conditions considered together) are plotted in Fig. 13 as a function of span. As expected, the soft-inplane rotor system produces significantly lower dynamic loads. A reduction of approximately 50% in the highest (midspan) loads is indicated on the plot.

7 CONCLUSIONS

An experimental study of a new four-bladed, semi-articulated, soft-inplane hub designed for the WRATS tiltrotor testbed was conducted in hover and forward flight. Based on results of the tests, the following conclusions are indicated:

1. The lag-mode frequency and damping of the new soft-inplane rotor system were measured and found to be representative what can be obtained at full-scale.

2. In hover, the new soft-inplane rotor system produced adequate levels of damping throughout the rotor speed spectrum. Ground resonance does not appear be a problem for the current soft-inplane design.

3. In windmilling airplane mode, damping levels for the new soft-inplane rotor system were extremely low and insufficient for full-scale application.

4. For the soft-inplane rotor, there is a large increase in system damping associated with moving from the windmilling to the powered-mode operating condition. For the baseline stiff-inplane design, subcritical damping increases, but there is not a significant change in the stability boundary.

5. The GPC-based active stability augmentation system was very effective at increasing damping in all the fundamental wing modes simultaneously, for both the soft-inplane and stiff-inplane rotor systems.

6. The GPC controller was very robust with respect to rotor speed and airspeed, with the system damping for the stiff-inplane rotor still increasing at 45 knots beyond the corresponding open-loop instability condition.

7. A substantial reduction of blade and hub dynamic loads was obtained for the new soft-inplane design as compared to the baseline stiff-inplane design during conversion mode operations.

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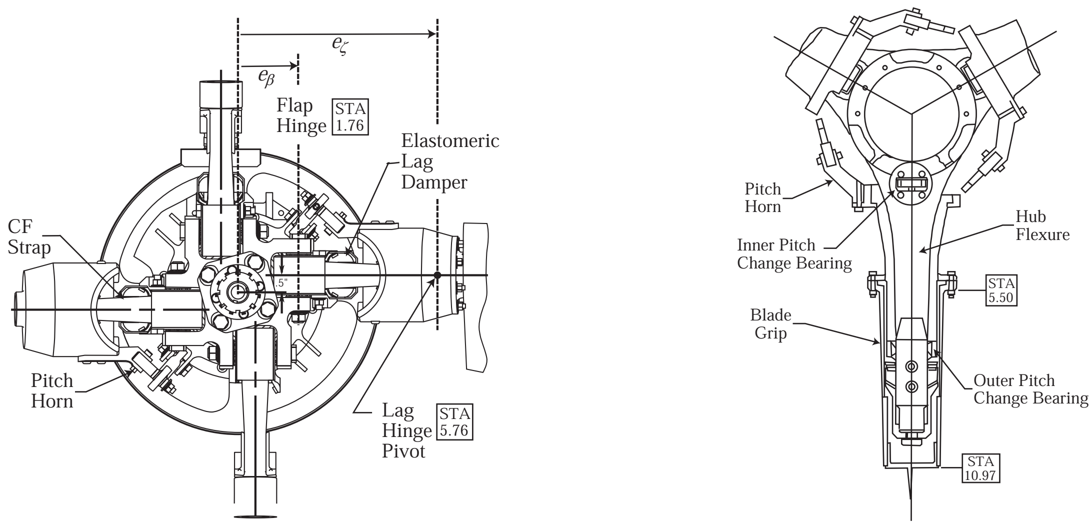
Table 1: Key rotor system properties.

Parameter	Baseline 3-bladed	Soft-Inplane 4-bladed
Radius	45.6 in	45.7 in
Twist[1]	47.5°	47.5°
Rotor Weight[2]	14.59 lb	16.94 lb
Hub Weight[3]	7.189 lb	9.703 lb
Blade Weight[4]	2.167 lb	1.770 lb
Blade Flap Inertia	0.2330 slug-ft^2	0.1265 slug-ft^2
Hover RPM	888	888
Cruise RPM	742	742
Airfoil start	8.0 in	7.5 in
Lift curve slope (nom.)	5.9/rad	5.9/rad
Tip chord	4.470 in	3.250 in
Root chord	6.510 in	4.190 in
0.75R chord	5.069 in	3.757 in
Solidity, σ [5]	0.106	0.105
Precone	2.50°	2.75° [6]
Geometric δ_3	-15.0°	+15.0°
Geometric δ_4	–	+9.0°
Hub gimbal spring constant	0.488 ft-lb/deg	–

[1]Distribution is nonlinear.
[2]Includes all blades, hub, pitch links, and hub attachment to mast hardware.
[3]Includes hub, nose cone, pitch links, bearings, and blade cuffs.
[4]Per blade, from hub attachment point outboard, includes ballast weight inserts.
[5]Based on chord at 75% radius.
[6]This number has little meaning for the current study because there was no flap hinge spring.



(a) The 4-bladed semi-articulated soft-inplane hub.

(b) The 3-bladed gimballed stiff-inplane hub.

Fig. 1. Schematics of the two hub types tested.

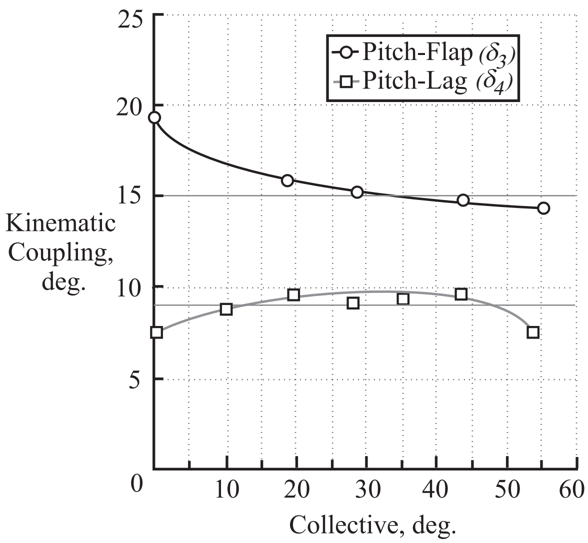


Fig. 2. Soft-inplane control system kinematic couplings as a function of collective pitch.

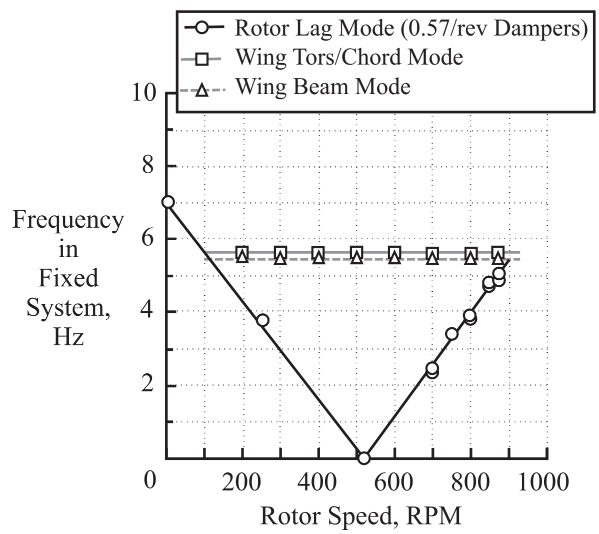


Fig. 3. Frequencies of the three dominant coupled-system modes as a function of rotor speed.

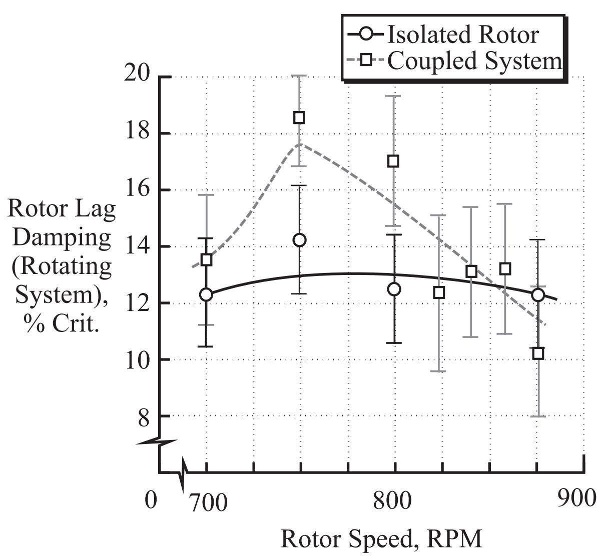


Fig. 4. Rotor lag mode damping as a function of rotor speed (0.57/rev damper set).

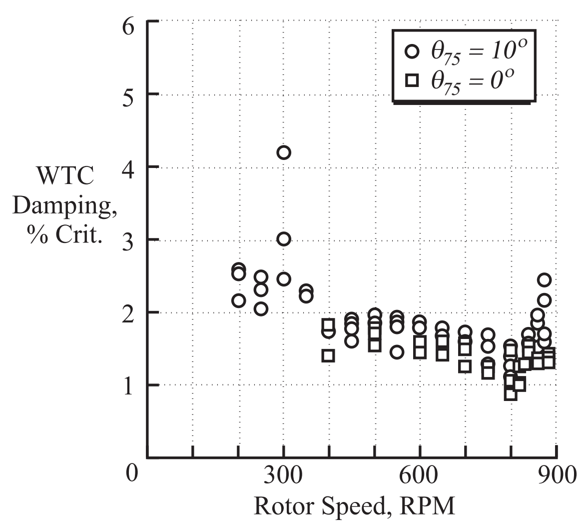


Fig. 5. Wing torsion/chord mode (WTC) damping as a function of rotor speed (0.57/rev damper set).

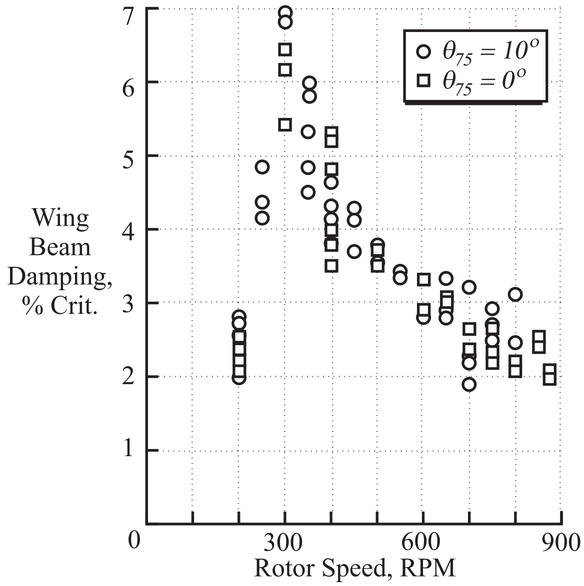


Fig. 6. Wing beam mode damping as a function of rotor speed (0.57/rev damper set).

Fig. 7. The four-bladed soft-inplane rotor mounted on the WRATS testbed for airplane mode testing in the TDT.

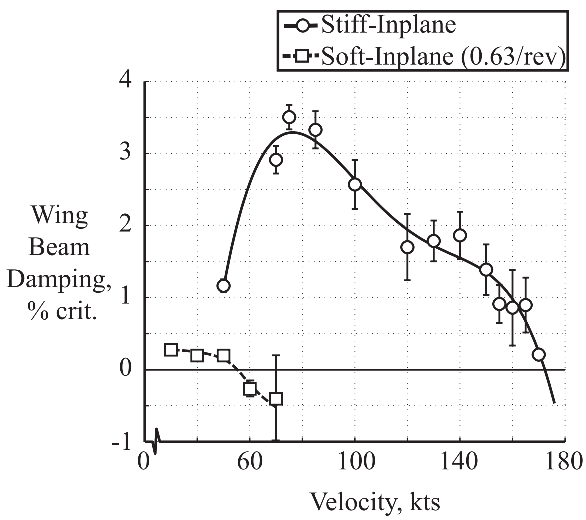


Fig. 8. Comparison of wing beam mode damping between the soft-inplane (0.63/rev damper set) and the stiff-inplane rotor system (742 RPM, off-D/S, windmilling).

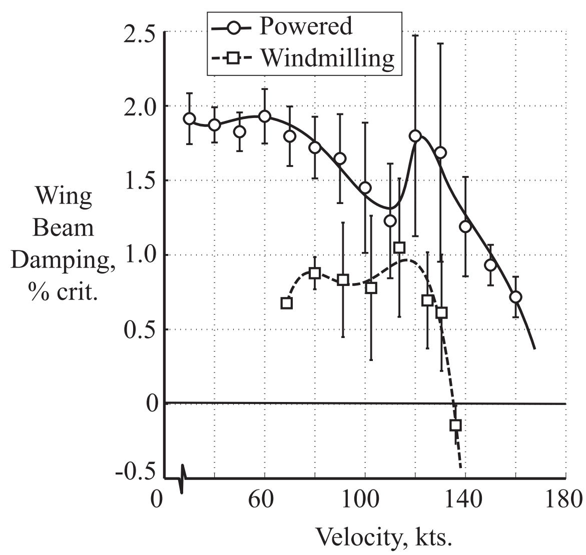


Fig. 9. Comparison of wing beam mode damping between the windmilling and powered conditions for the soft-inplane rotor system (0.63/rev damper set, 742 RPM, on-D/S).

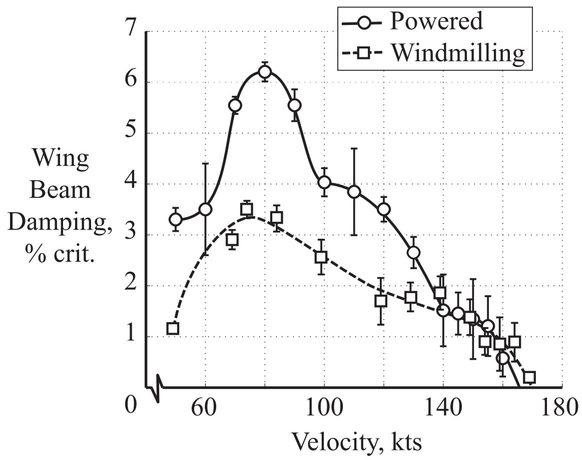


Fig. 10. Comparison of wing beam mode damping between the windmilling and powered conditions for the stiff-inplane rotor system (742RPM, off-D/S).

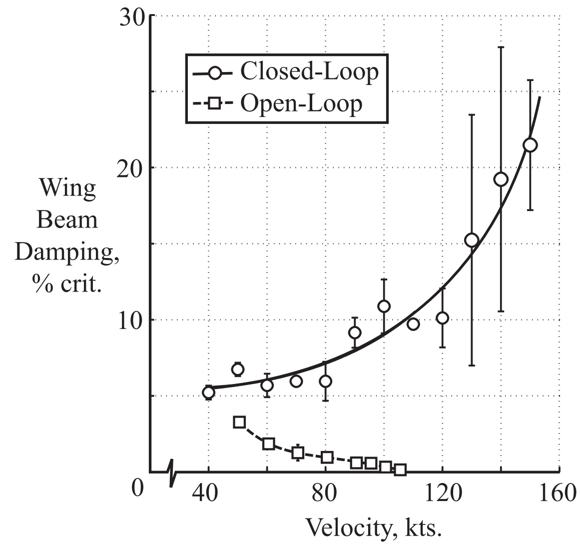


Fig. 11. Effect of GPC active stability augmentation on wing beam mode damping for the stiff-inplane rotor system (742 RPM, off-D/S).

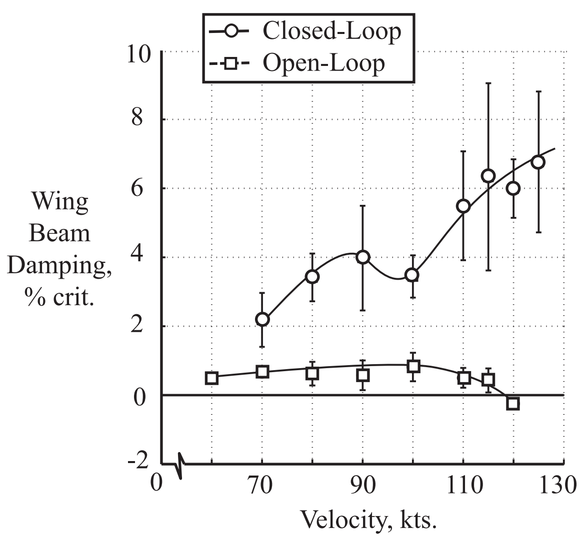


Fig. 12. Effect of GPC active stability augmentation on wing beam mode damping for the soft-inplane rotor system (742 RPM, on-D/S, wind-milling, 0.63/rev damper set)

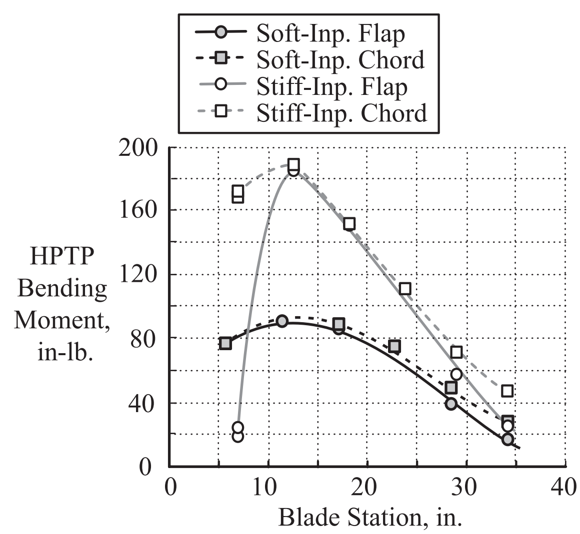


Fig. 13. Effect of hub type on blade dynamic loads (half-peak).